ROCKETDYNE

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DESIGN AND ANALYSIS OF A
7-INCH LIQUID HYDROGEN CHECK
VALVE FOR THE ROCKETDYNE MODEL
NFS-3B FEED SYSTEM

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FOREWORD

This topical report summarizes the analysis,
design, and water flow tests conducted under
Contract NASw-1210 (Development of Phoebus
Feed Systems) of a 7-inch liquid hydrogen
check valve for use in the discharge ducting
of the Rocketdyne Model NFS-3B Liquid Hydrogen
Feed System used in testing of the Phoebus 1
and Phoebus 2 reactors at the Nuclear Rocket
Development Station.

The original vendor configuration of the check
valve and subsequent modification to the final
design are described.

This report was prepared by S. C. Laxineta and
R. F. Searle in accordance with requirements of
contract NASw-1210.

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INTRODUCTION AND SUMMARY

In April 1966 procurement was initiated for two 7-inch liquid hydrogen check valves which were to be used in the discharge ducting of the Phoebus NFS-3B Feed System. The primary valve function is to prevent reverse flow of liquid hydrogen through the turbopump into the inlet duct during emergency shutdown of the system. The detail parts and assembly for the final valve configuration are shown in Fig. 1 through 3. Overall valve diameter is 11.625 inches with an overall length of 16 inches. The seat diameter is 7 inches.

Design of the procured valves conformed to the basic configuration proposed by the vendor except for two modifications which resulted from customer and Rocketdyne review of the proposed configuration. These modifications were use of an all metal seat in place of a soft seat and addition of a third brace to stiffen the poppet guide.

Acceptance flow tests with water of the first valve received from Flomatics, Inc. revealed that the valve poppet was hydrodynamically unstable at flows greater than 85 percent of the design rating. A partial fix for the problem was accomplished by limiting the poppet stroke. Instability still occurred in water tests but amplitude was reduced. One valve was delivered with this temporary fix while Rocketdyne continued efforts to obtain a permanent solution to the problem.

The flow geometry of the valve was redesigned using information obtained from flow analysis of the original configuration and data obtained from water flow tests of a variable geometry test model which was built up from parts of the second valve. During this period new information on expected closing and opening rates of the valve in service became available from dynamic studies. The requirements from these studies, which

were more severe than those previously in use, were utilized in completing the redesign.

A final design configuration valve was fabricated, successfully flow tested at Rocketdyne, and delivered. This configuration is illustrated in Fig. 7 .

DISCUSSION

The design of the check valve procured from Flomatics, Inc., is shown in Fig. 1. The valve has an overall diameter of 11.625 inches with an overall length of 16 inches. The seat diameter is 7 inches. It retained the basic configuration originally proposed by the vendor. However, two modifications were incorporated in the valve as a result of customer and Rocketdyne review. These modifications were substitution of a metal seat for the proposed elastomeric seat and addition of a third spoke in the poppet guide. 300 series stainless steel was used for all valve parts with the exception of the poppet shaft bearings which were fabricated from Kel F. The rated flow was 150 pounds per second liquid hydrogen with a maximum Δ P of 10 psi. A conical metal seat was used to effect shutoff within the allowable leakage requirement which was specified as 1.0 lb/sec helium gas at 2250 psig and -320 °F.

Two valve assemblies were ordered from Flomatics, Inc. The first valve successfully passed the leakage test at the vendor's plant with an ambient leakage rate of 3 cc/min and a rate of 35 cc/min at -320 °F. This valve was then shipped to a Los Angeles test laboratory, Byron Jackson, Inc., for waterflow testing. During this waterflow testing the check valve exhibited a flow instability at a frequency of approximately 1 to 3 cps with an amplitude sufficient to cause limit cycling of the poppet. This instability occurred at a waterflow rate of approximately 3500 GPM which is equivalent to a liquid hydrogen flow rate of 130 pounds per second which corresponds to 85% of rated flow.
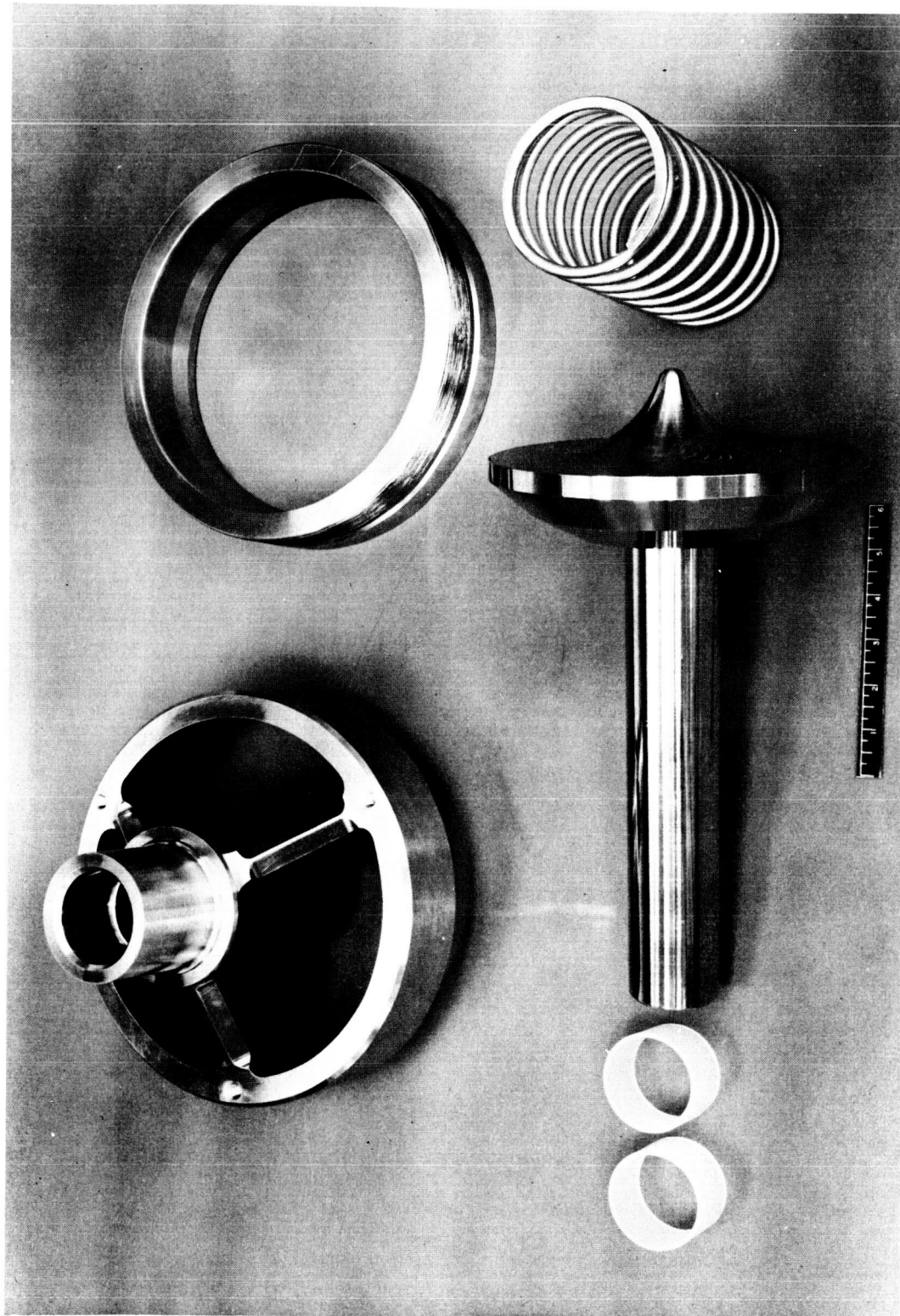
Figure 1. Poppet and Support of 7-Inch Liquid Hydrogen Check Valve
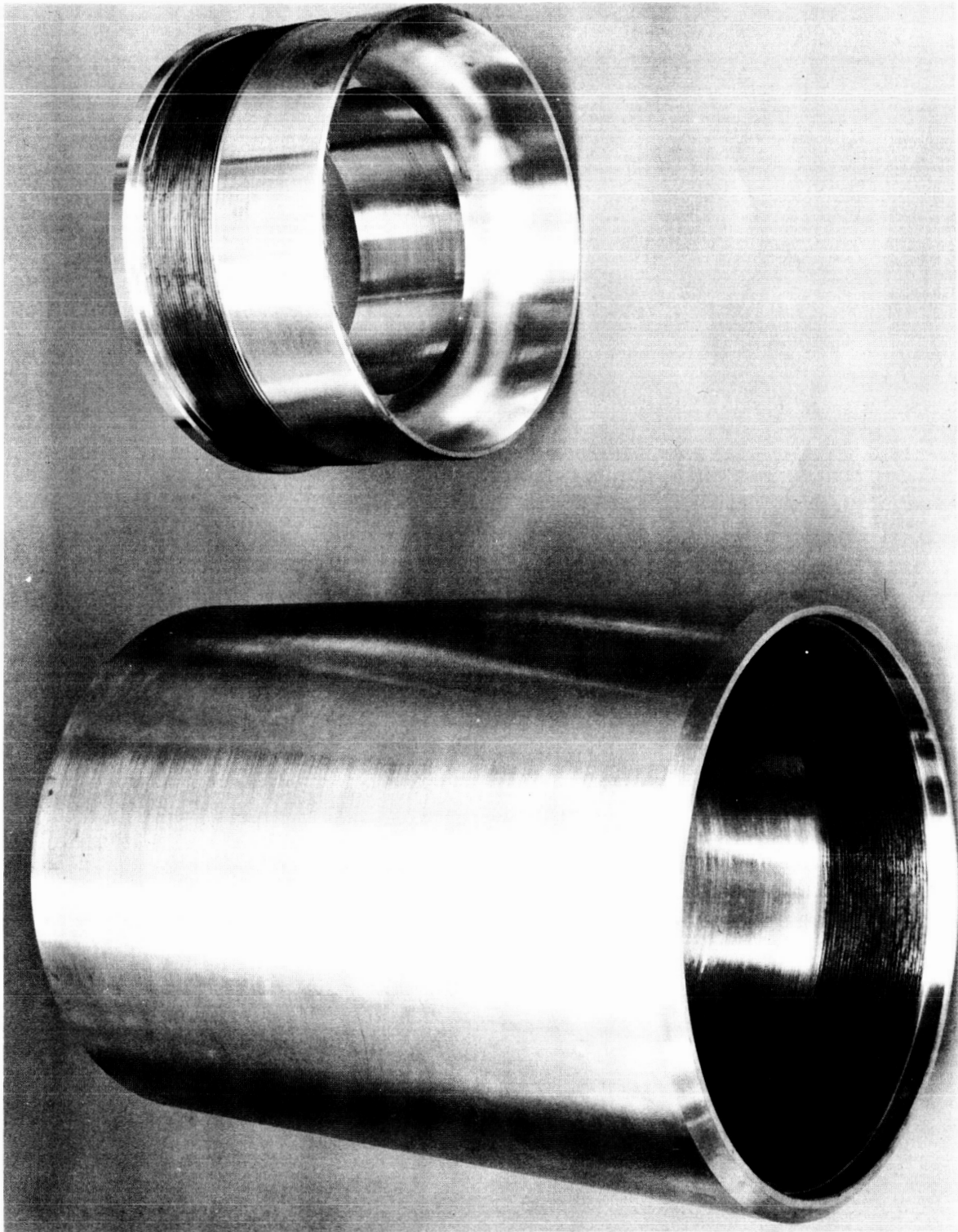
1XZ62-3/14/67-C1C

1XZ62-3/14/67-C1A

Figure 2. Seat and Housing of 7-Inch Liquid Hydrogen Check Valve

1XZ62-3/14/67-C1B

Figure 3.   7-Inch Liquid Hydrogen Check Valve Assembly
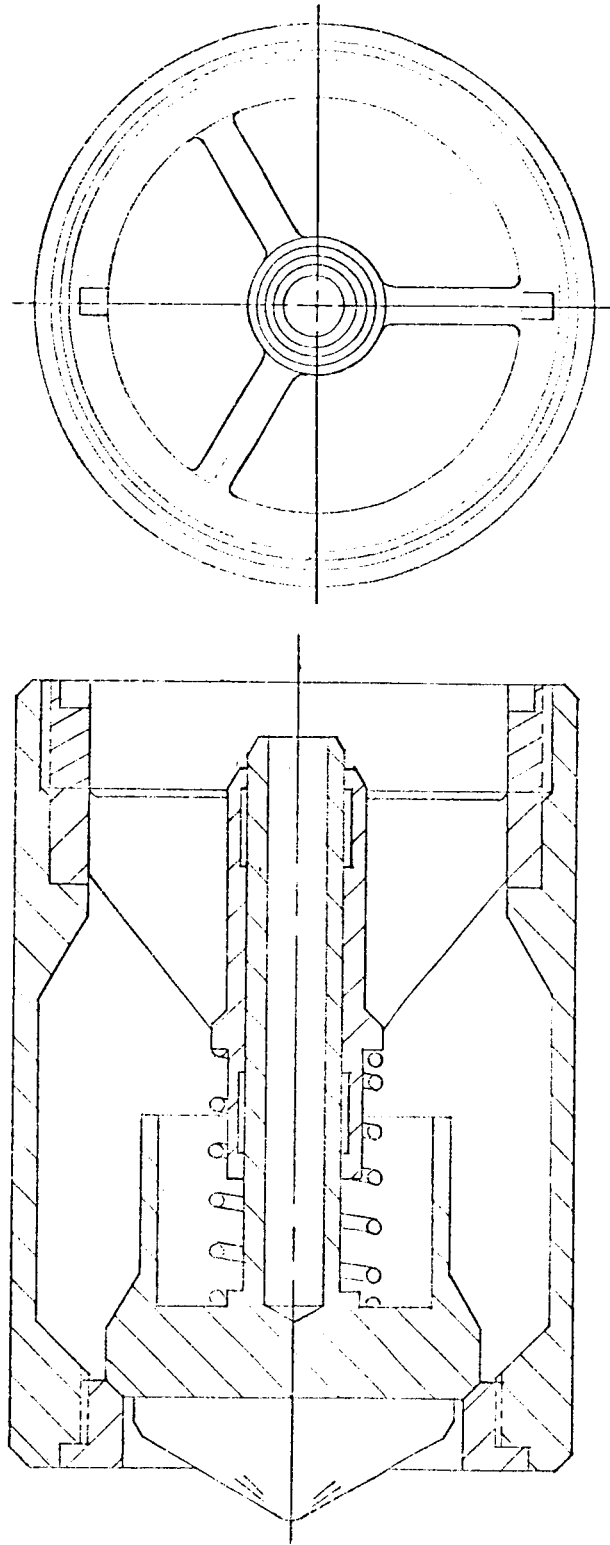
Figure 4. Original Configuration Valve

An analysis was performed to determine the cause of the instability. Results of the analysis indicated that a force balance reversal occurs across the poppet due to downstream velocity pressure recovery at certain valve positions. This velocity pressure recovery phenomenon created a static pressure differential acting on the poppet area tending to close the valve. As the poppet approached the seat, however, the energy loss across the poppet increased sufficiently to overcome the pressure recovery and reverse the unbalanced force to the opening direction. This force direction reversal as a function of poppet position coupled with the large mass of the poppet (40 lb) was responsible for the limit cycling of the poppet from the full open to full closed position. Had the poppet been considerably lighter the overshoot might have been reduced sufficiently to prevent metal to metal contact.

A redesign effort was undertaken to provide a stable valve configuration. At the same time an interim fix was attempted by adding spacers to the poppet shaft to shorten the valve stroke. Some improvement was noted at a stroke of 1-5/8 inch in the form of reduced amplitude (limit cycling ceased) although the instability was not eliminated. A valve with a spacer installed to limit stroke to 1-5/8 inch was delivered to NRDS for initial testing while the redesign was being completed.

The redesign configuration utilized both kinetic energy transfer and pressure-area developed force for maintaining a constant direction force balance. The kinetic energy transfer was accomplished by changing the direction of incoming flow a full 90 degrees instead of the 60 degrees used in the original design. This produced considerable additional force as shown by the equation for the turbine blade analogy below:
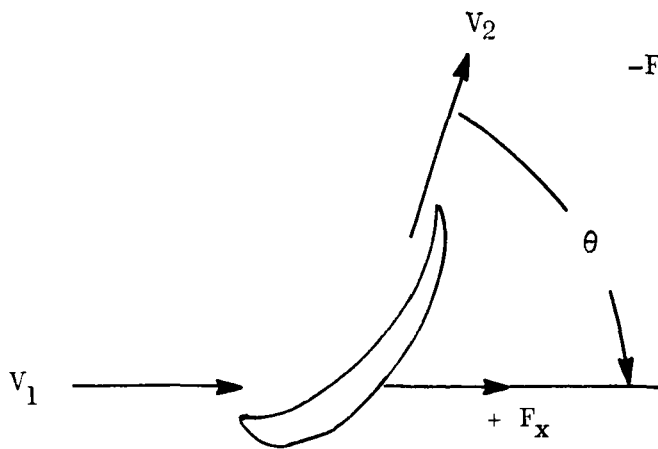
$$-F_x = Q \in (V_2 \cos \theta - V_1)$$

$-F_x$ = force exerted by fluid on blade in x or axial direction

Q = flowrate in ft^3/sec

$\in$ = density in lbs/ft^3

$\cos 60 \deg = 0.5$

$\cos 90 \deg = 0$

Consequently, if the magnitude of V_2 equals the magnitude of V_1, the force on the 90 degree poppet is double the force on the 60 degree poppet. Also, since the smallest flow area in the Flomatics design occurs at the seat, V_2 is large compared with V_1 thus further reducing the opening force.

The pressure-area force is developed by creating a restriction around the poppet perimeter which provides an energy loss to compensate for the pressure recovery downstream of the poppet.

A variable geometry water flow test unit, shown in Fig. 5, was fabricated using components from the second valve assembly ordered from Flomatics. The unit was tested at various poppet stroke positions and annulus widths in both the opening and closing directions to verify stability and provide pressure drop data. Results of the Δ P vs stroke tests are plotted in Fig. 6. They are normalized to a liquid hydrogen flowrate of 150 pounds per second. Annulus widths of 1 inch and 7/8 inch were used along with stroke positions ranging from 3/8 to 1-7/8 inches. All configurations were stable.

At the inception of the program little information was available on expected check valve closing and opening rates. Approximately at the same
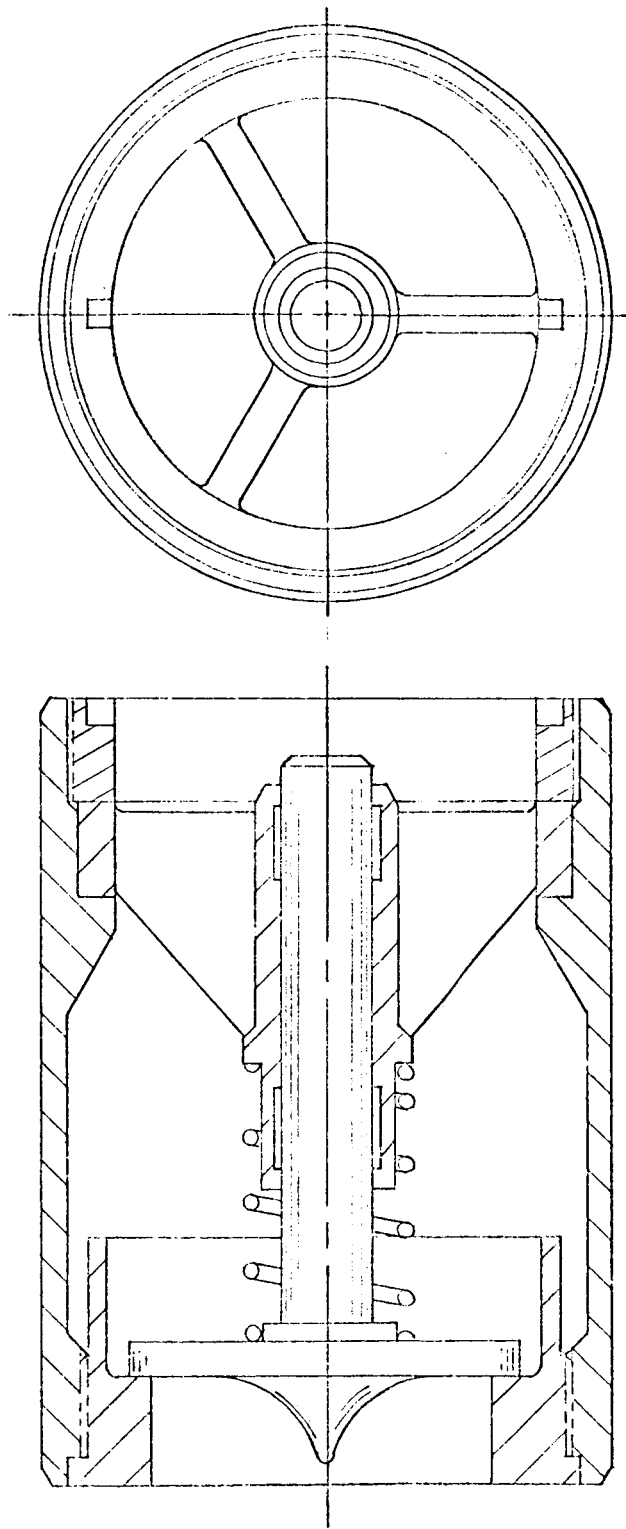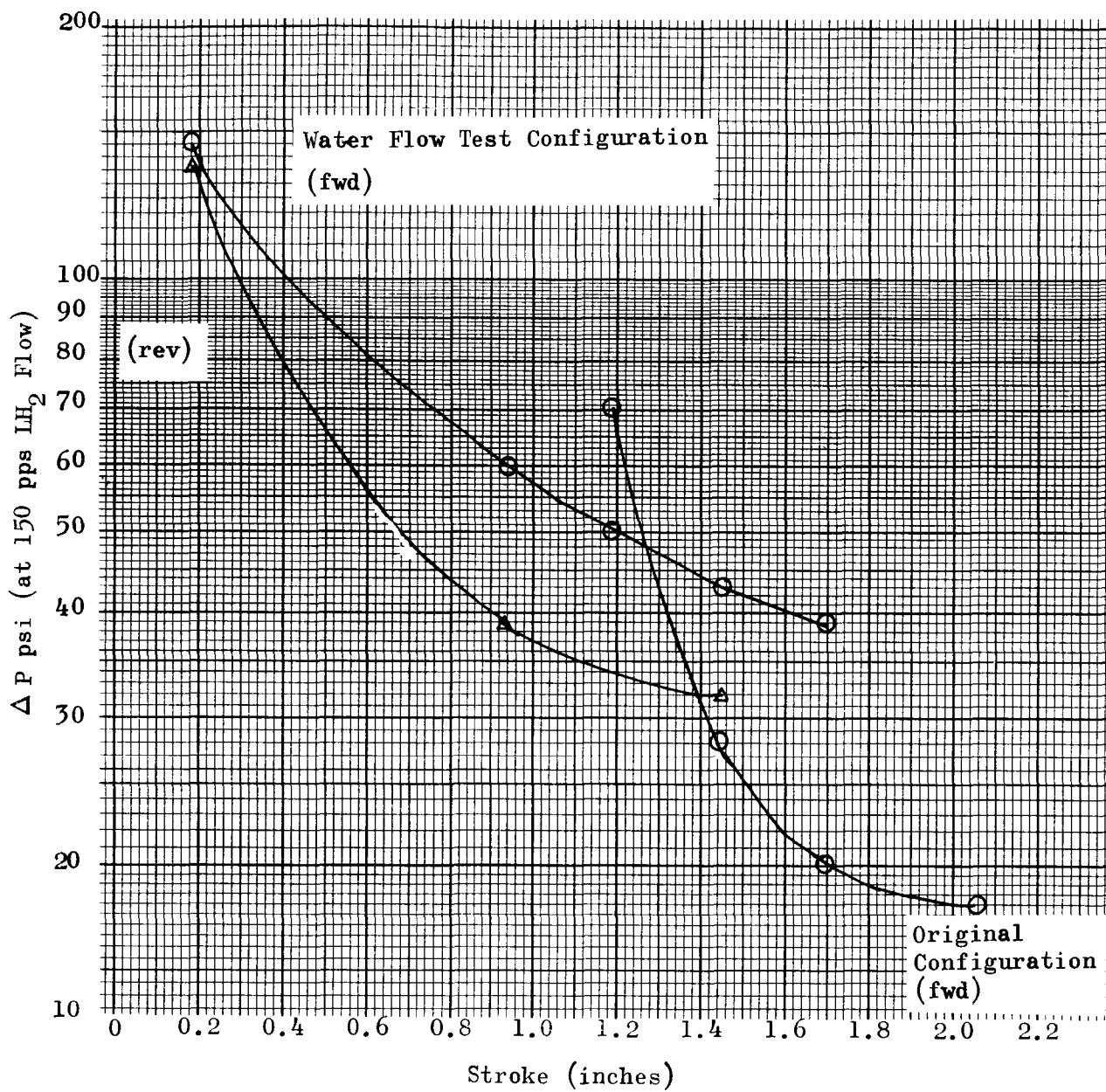
Figure 5. Water Flow Test Configuration Valve

Figure 6. Δ P vs Stroke Tests

time check valve redesign was being initiated checkout was completed on
the digital dynamic model of the feed system with check valves. Simula-
tion results from this model indicated that check valve closing and open-
ing velocities at end of travel might be as great as (325) in./sec and
(370) sec. This was considerably higher than originally anticipated.

The final valve design was selected on the basis of flow stability and
structural integrity analysis. Inconel 718 was selected for the poppet
seat of guide to increase strength because of dynamic stress considerations.
A discussion of the stress analysis is presented in the appendix. The
final configuration, shown in Fig. 7, incorporates a solid cylindrical
spring as the seat which deflects to reduce impact loading to an accept-
able level. Valve stroke is 1-3/4 inches which is 1/2 inch less than
Flomatic's design. The shorter stroke results in a lower impact velocity,
thus reducing the momentum which must be absorbed by the poppet and seat
or guide.

The 300 series stainless steel body was salvaged from the original Flo-
matics unit by machining rework of a relatively minor nature.

A tabulation of requirements for the final valve configuration is pre-
sented in Table I.

The final valve configuration was subjected to acceptance testing at
Rocketdyne. Waterflow test data is plotted in Fig. 8. Operation was
stable at all flows up to the design point. Valve leakage at 2250 psig
and ambient temperature (70 F) was measured and found to be below
100 SCIM. Leakage was not measured at low temperature due to a problem
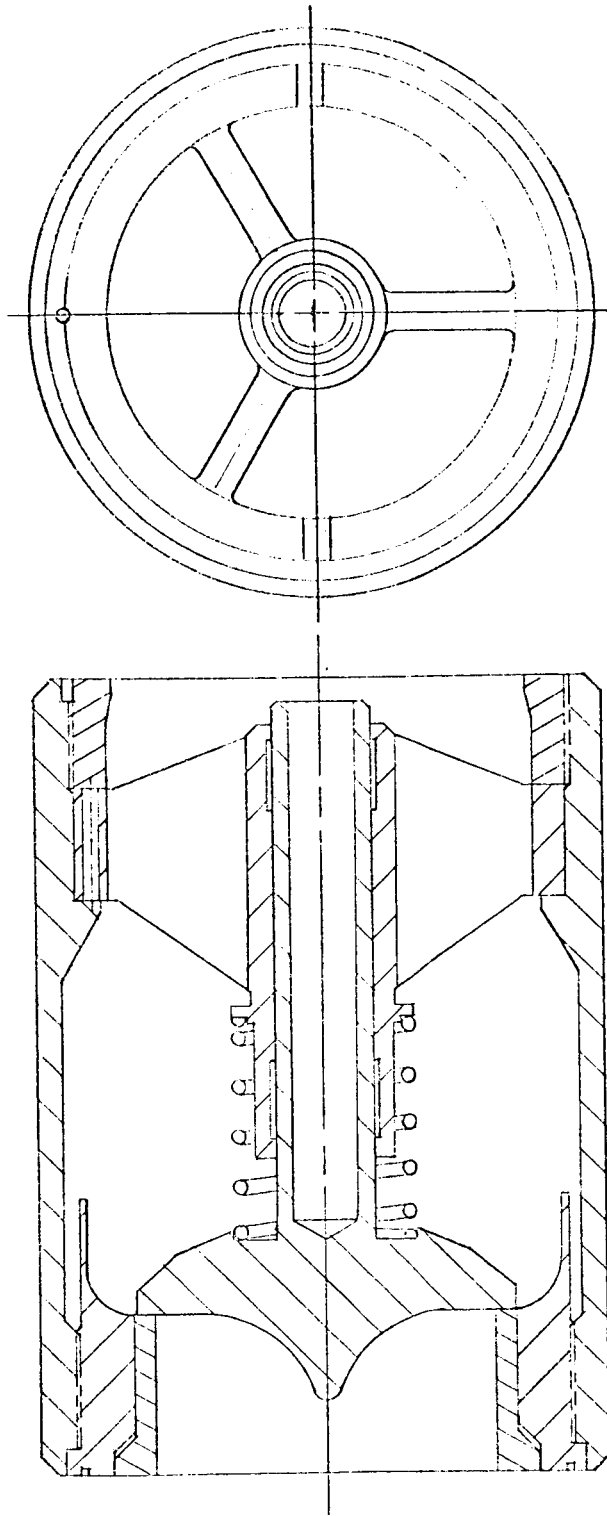with fixture seals which limited attainable pressure to approximately
400 psig.

Figure 7.   Liquid Hydrogen Check Valve

TABLE 1

99-108425 CHECKVALVE PERFORMANCE
AND ACCEPTANCE REQUIREMENTS

PERFORMANCE REQUIREMENTS

Fluid Pressures

Operating	2250 psig static
	2590 psig surge
Proof (at room temp. 70 ±10 F)	2350 ±50 psig
Burst (at room temp.)	6600 psig

Flow Characteristics

Cracking Pressure	2 psig max.
Reset Pressure	0 psig min.
Design Flowrate	150 lb/sec liquid hydrogen
Pressure Drop at Design Flow	50 psi

Leakage Rate With Helium Across Seat

Room Temp. (70 ±10 F)	1 lb/sec H_e @ 2250 psig
Colt Temp. (-310 ±10 F)	1 lb/sec H_e^e @ 2250 psig

Loading (Vibration & Impact)

Valve Poppet Max. Closing Impact	325 in./sec Velocity
Valve Poppet Max. Opening Impact	370 in./sec Velocity
Vibration	TBD

Materials

Housing, Spring, & Seat Bushing	300 Series Stainless
Poppet Guides	Kel-F
Other Parts	Inco-718

Life

Checking Cycles Between Refurbishments	200

ACCEPTANCE TEST REQUIREMENTS

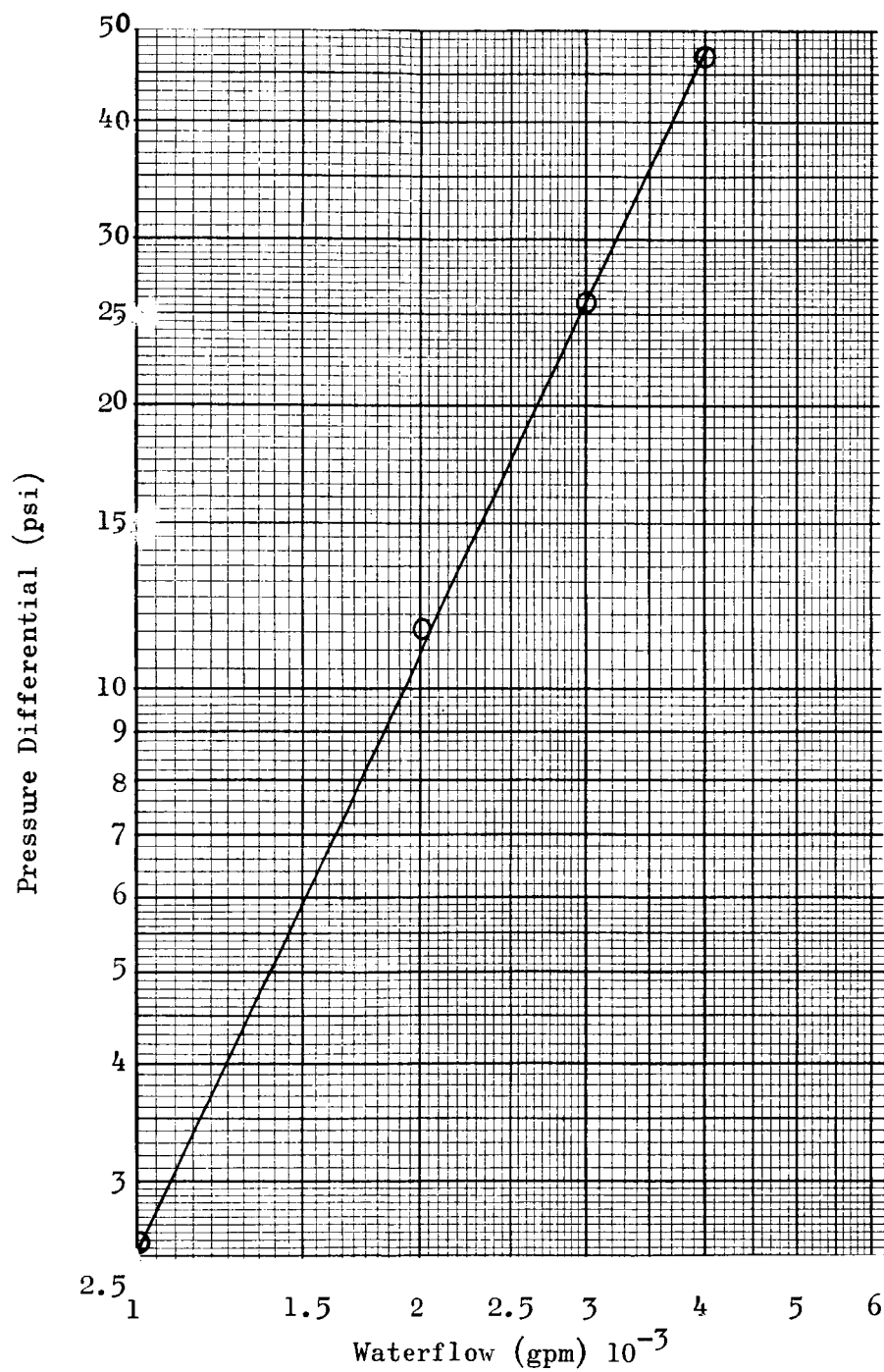|	
Proof Pressure (room temp.)	2350 psig water
Leakage (room temp. & -320 F)	1.0 #/s H_e @ 2250 psig
Cracking Pressure (-320 F)	2 psig max.
Water Flow (room temp.)	Δ P vs 2000 GPM, 3000 GPM, 4000 GPM 50 psi max. @ 4000 GPM

Figure 8. Pressure Differential vs Flow
(Acceptance Test Data)

NOTE: 4000 gpm Waterflow Corresponds to an LH_2 Flow of
Approximately 150 lb/sec

CONCLUSIONS AND RECOMMENDATIONS

The valve should be subjected to liquid hydrogen flow testing to verify
its stability and obtain a correlation of water and LH_2 pressure drop data.
This recommendation is made to reduce the element of doubt concerning whether
water flow testing adequately simulates the dynamic and static flow forces
which will be encountered during LH_2 flow tests.

The digital system simulation should be updated to define check valve
closing and opening velocities utilizing the final design characteristics
of the check valve as input data.

APPENDIX

STRUCTURAL ANALYSIS SUMMARY
POPPET TYPE CHECK VALVE ASSEMBLY
P/N 99-108425

Structural analysis, of the Poppet Type Check Valve Assembly, P/N 99-108425, indicated that the final design is structurally adequate. Consideration was given to the dynamic loading of the poppet opening and closing at high velocities and internal pressure. The valve was structurally analyzed for a closing velocity of 325 inches/second, an opening velocity of 370 inches/ second, and pressures of 2000 psi. These velocities were established by Systems Design Unit based on analog computer studies of the poppet dynamic response under flow conditions. During the initial design stage, various energy absorbing devices were considered such as belleville springs, and laminated poppet. These proved to be structurally inadequate and were therefore eliminated.

The final design absorbed all the poppet closing energy with a cylindrical tube poppet seat, P/N 99-108428. The poppet, P/N 99-108426, was sized with the necessary thickness to resist the impact force. During the opening cycle the poppet support structure, P/N 99-108423, was sized to absorb the opening poppet energy. In order to meet the strength requirement, the material selected for the poppet, seat, and support structure was INCO-718.

Material Properties INCO-718 (RA0111-019)

	70°F	LH_2 Temp.
F_{tu}	175,000	222,000
F_{ty}	145,000	170,000
E	29.5×10^6	32×10^6

The maximum stress on the seat due to impact and pressure load = 146,000 psi

$$\text{Ultimate safety factor} = \frac{222,000}{146,000} = 1.51$$

Calculated maximum stress in the poppet at the edge of the stem = 143,700 psi

$$\text{Ultimate safety factor} = \frac{222,000}{143,700} = 1.55$$

The maximum stress in the poppet stem guide = 118,200 psi

$$\text{Ultimate safety factor} = \frac{222,000}{118,200} = 1.96$$

All other areas of the check valve are structurally adequate for the pressure and poppet dynamic loads and have stresses lower than those shown. The material properties at LH_2 temperatures were used because, as specified by the Systems Design Unit, the valve will always be at LH_2 temperatures during the dynamic loading conditions.

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13. ABSTRACT

This topical report summarizes the analysis, design, and water flow tests conducted under Contract NASw-1210 (Development of Pheobus Feed Systems) of a 7-inch liquid hydrogen check valve for use in the discharge ducting of the Rocketdyne Model NFS-3B Liquid Hydrogen Feed System used in testing of the Phoebus 1 and Phoebus 2 reactors at the Nuclear Rocket Development Station.

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